Chiral & trace anomalies in Deep Virtual Compton Scattering

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In Collaboration with:

Yoshitaka Hatta (BNL)
Werner Vogelsang (Tubingen U.)

Based on: arXiv:2210.13419

Center for Frontiers in Nuclear Science

Stony Brook University

CFNS Monthly Postdoc Meetings

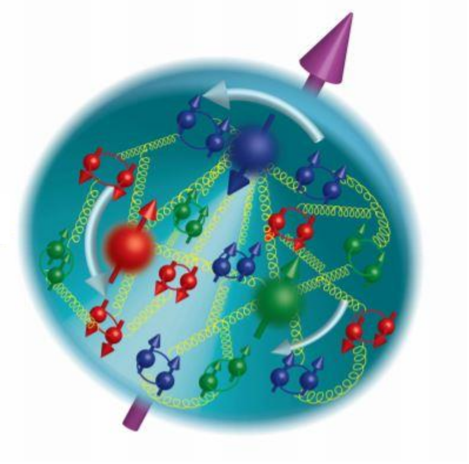
Quantum Chromodynamics (QCD)

- Interested in nucleons (protons & neutrons)

- Deep-inelastic electron-proton scattering (Friedman, Kendall, Taylor et al, 1968)

  --- Protons are complicated dynamical systems of quarks and gluons (partons)

- Pressing question: How to understand nucleons from its constituents?



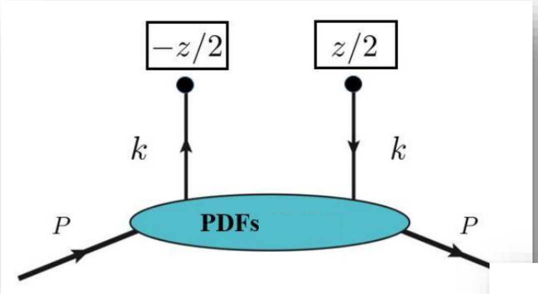
(EIC White Paper)

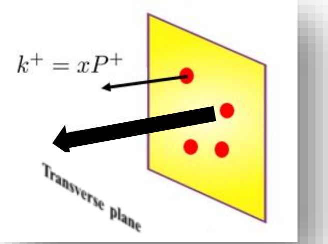
Quantum Chromodynamics (QCD): Non-perturbative functions

Parton motion

Nucleon motion

Snapshots of the nucleons





Parton Distribution Functions

PDFs (x)

Quantum Chromodynamics (QCD): Non-perturbative functions

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Nucleon motion

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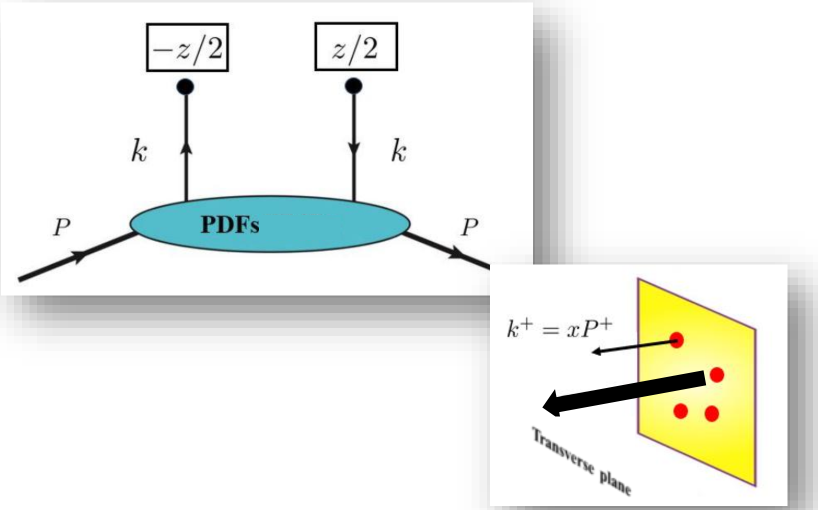
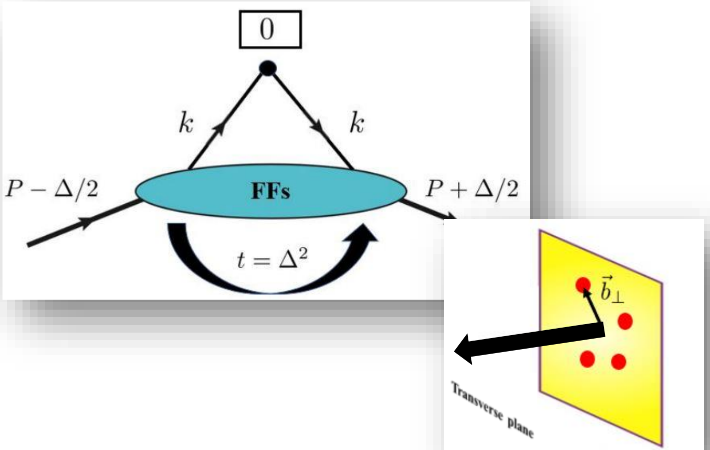


PDFs (x)

Form Factors

FFs (Δ)



Quantum Chromodynamics (QCD): Non-perturbative functions

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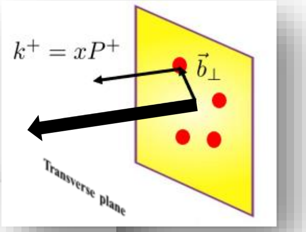
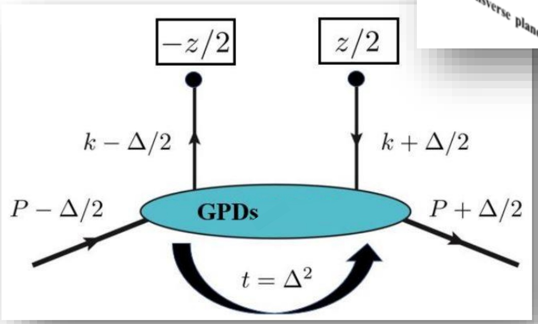
Nucleon motion

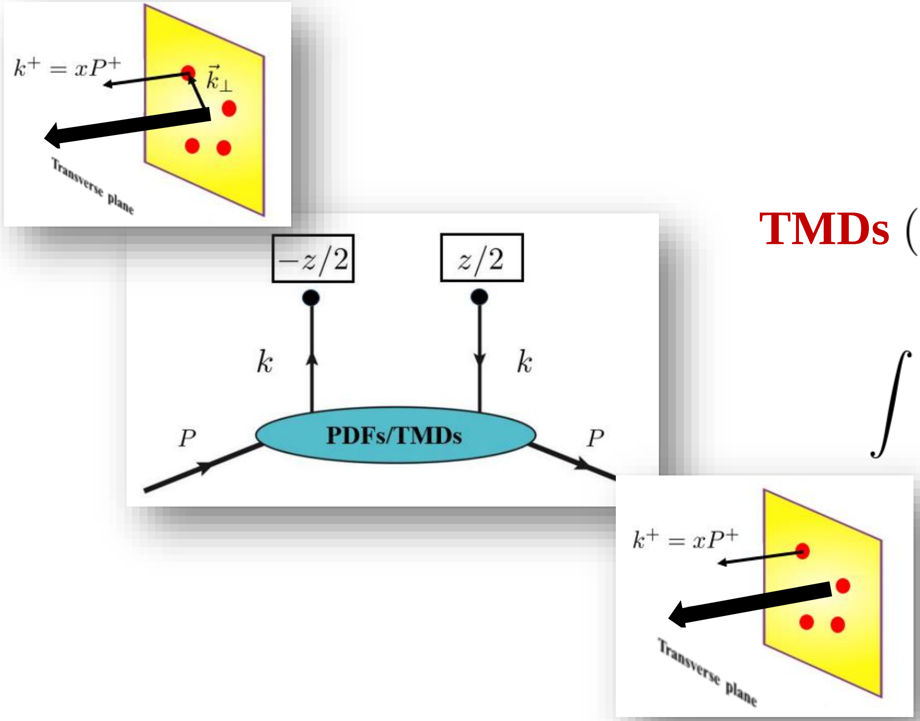
Snapshots of the nucleons

Generalized Parton Distributions





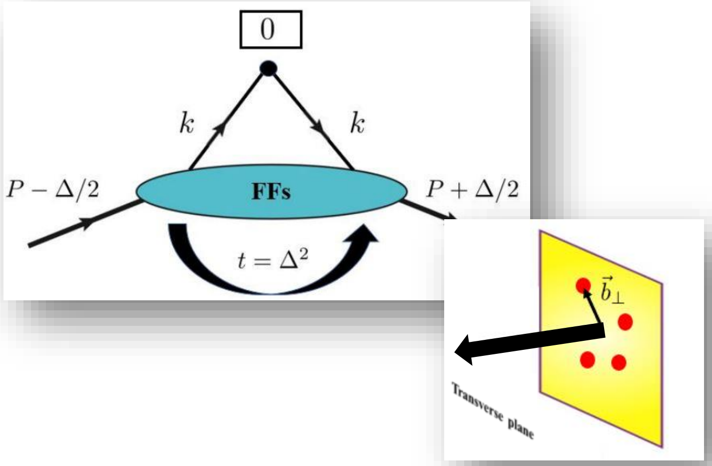
Transverse Momentum-dependent Distributions



TMDs $(x, \vec{k}_\perp)$ $\quad$ **GPDs** (x, Δ)

$\int d^2\vec{k}_\perp$ $\quad$ $\Delta = 0$ $\quad$ $\int dx$

PDFs (x) $\quad$ **FFs** (Δ)



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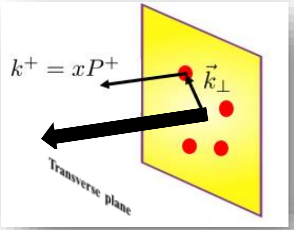
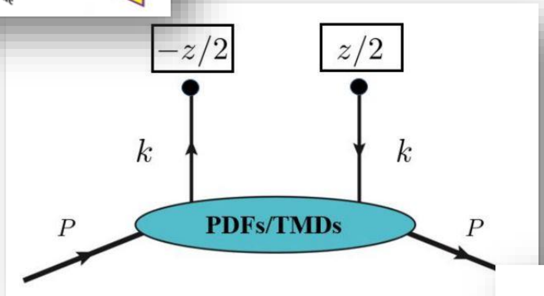
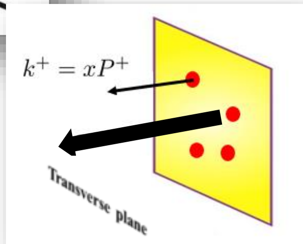
Generalized Transverse Momentum-dependent Distributions







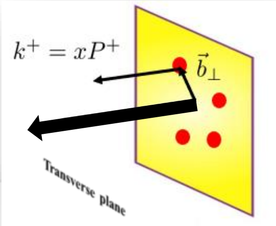
GTMDs $(x, \vec{k}_\perp, \Delta)$

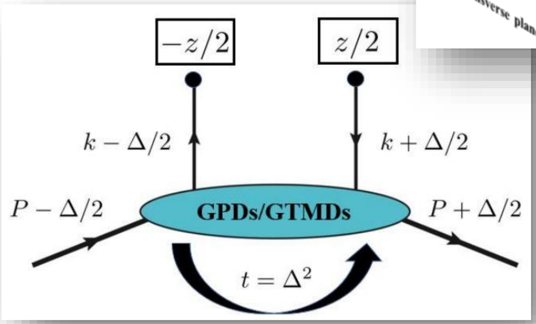
$\Delta = 0$ → **TMDs** $(x, \vec{k}_\perp)$

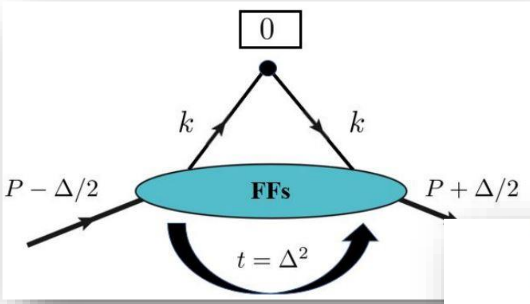
$\int d^2\vec{k}_\perp$ → **GPDs** (x, Δ)

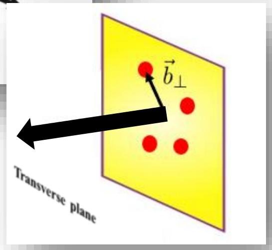
TMDs $(x, \vec{k}_\perp)$: $\int d^2\vec{k}_\perp$ → **PDFs** (x)

GPDs (x, Δ): $\Delta = 0$ → **PDFs** (x); $\int dx$ → **FFs** (Δ)









Quantum Chromodynamics (QCD): Non-perturbative functions

Parton motion

Nucleon motion

Snapshots of the nucleons

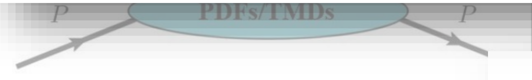
Generalized Transverse Momentum-dependent Distributions

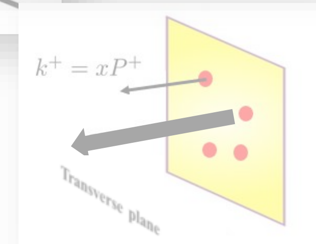
GTMDs $(x, \vec{k}_\perp, \Delta)$

$\Delta = 0$

Focus of this talk:

Manifestation of anomalies in high-energy exclusive processes



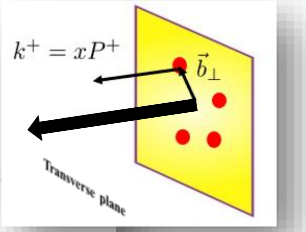


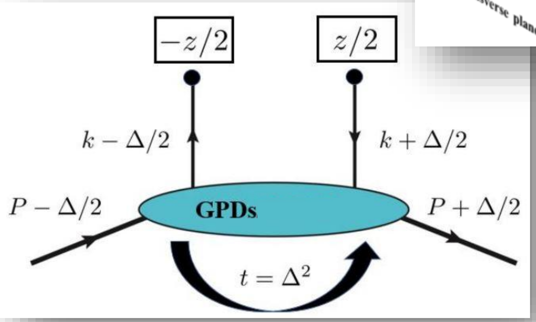
GPDs (x, Δ)

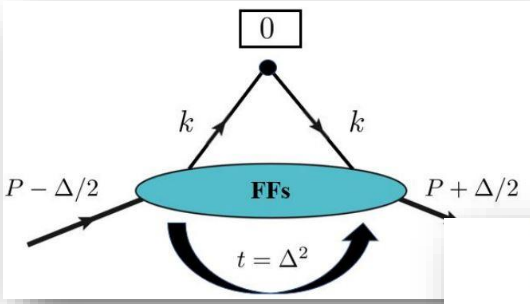
$\int dx$

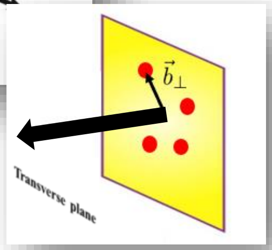
PDFs (x)

FFs (Δ)









Chiral anomaly

Recap on U(1) chiral anomaly in QCD:

- **Lagrangian invariant under global chiral rotation** $\psi \to e^{i\alpha\gamma_5}\psi$
- **Conserved charge** $J_5^\mu = \sum_f \bar{\psi}_f \gamma^\mu \gamma_5 \psi_f$

Chiral anomaly

Anomaly equation:

$$\partial_\mu J_5^\mu = -\frac{n_f \alpha_s}{4\pi} F^{\mu\nu} \tilde{F}_{\mu\nu}$$

A fundamental property of axial-vector current is the anomaly equation

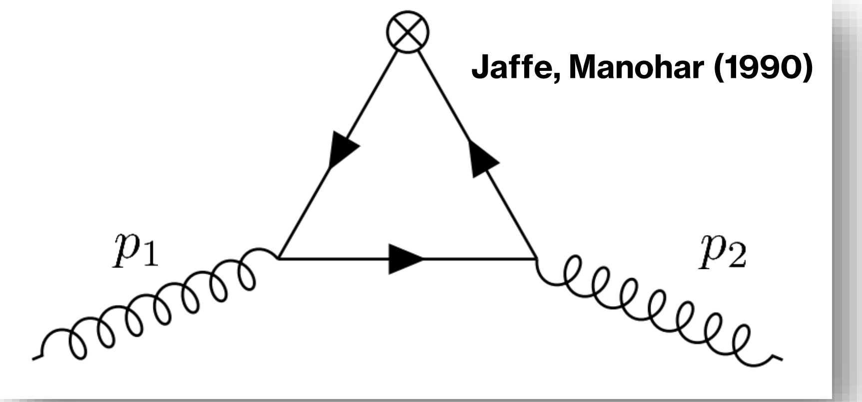
Chiral anomaly

Anomaly equation:

$$\partial_\mu J_5^\mu = -\frac{n_f \alpha_s}{4\pi} F^{\mu\nu} \tilde{F}_{\mu\nu}$$

A fundamental property of axial-vector current is the anomaly equation

A perturbative solution to anomaly equation:



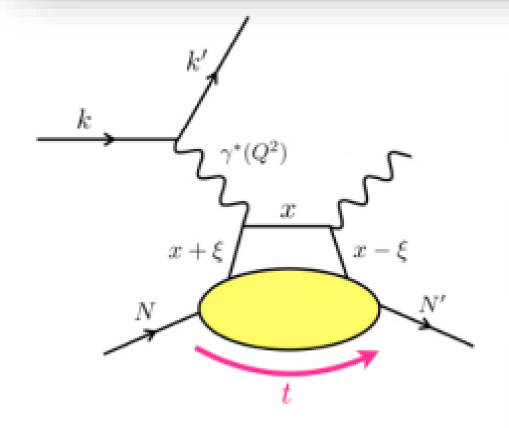
Calculation in off-forward kinematics $(l = p_2 - p_1)$**:**

$$\langle p_2 | J_5^\mu | p_1 \rangle = \frac{n_f \alpha_s}{4\pi} \frac{i l^\mu}{l^2} \langle p_2 | F_a^{\alpha\beta} \tilde{F}^a_{\alpha\beta} | p_1 \rangle$$

Triangle diagram is dominated by infra-red pole

Imprint of Anomalies in QCD Compton scattering

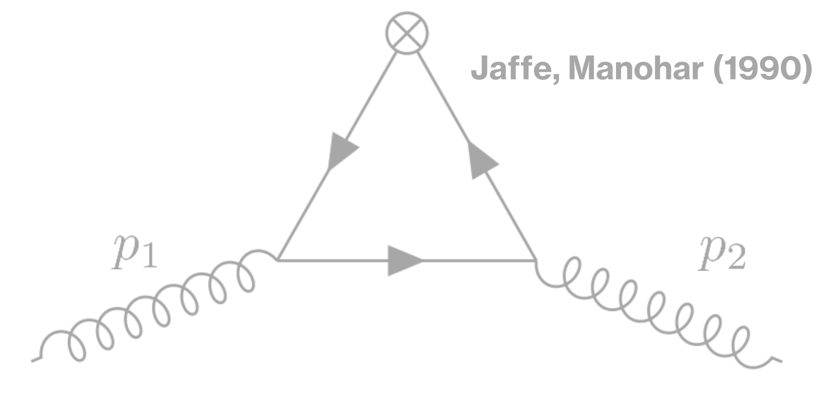
Compton scattering:



In QCD Compton scattering, box diagrams appear in perturbation theory at one-loop

Box diagram can be viewed as a non-local generalization of triangle diagram

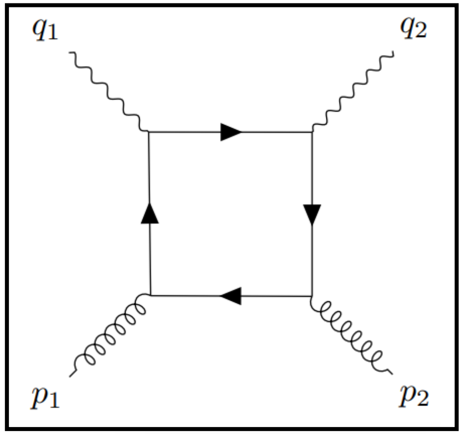
If triangle is dominated by anomaly pole, trace of that should be visible in box diagram



Calculation in off-forward kinema

$$\langle p_2|J_5^\mu|p_1\rangle = \frac{n_f\alpha_s}{4\pi}\frac{il^\mu}{l^2}\langle p_2|F_a^{\alpha\beta}\tilde{F}$$

Triangle diagram is dominated by



Box diagram

Imprint of Anomalies in QCD Compton scattering

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The role of the chiral anomaly in polarized deeply inelastic scattering I: Finding the triangle graph inside the box diagram in Bjorken and Regge asymptotics

Andrey Tarasov[1,2] and Raju Venugopalan[3]

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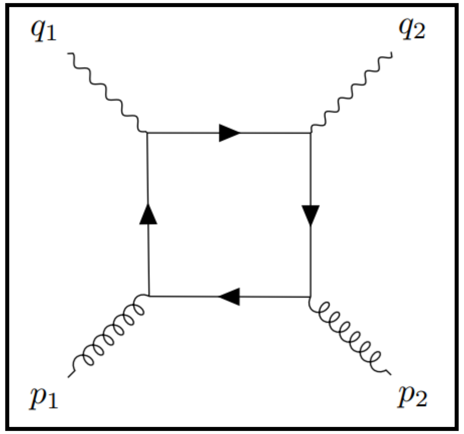
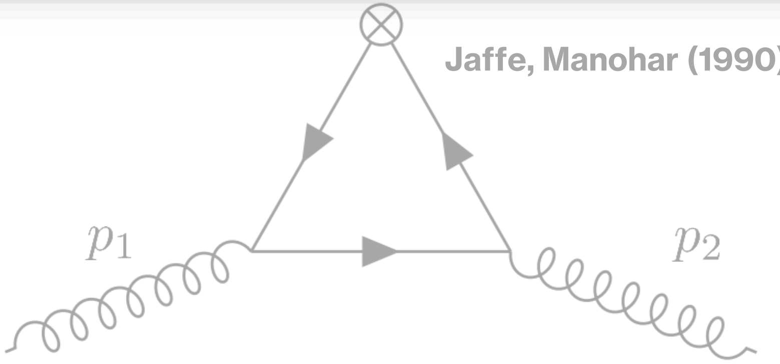
The role of the chiral anomaly in polarized deeply inelastic scattering II: Topological screening and transitions from emergent axion-like dynamics

Andrey Tarasov[1,2] and Raju Venugopalan[3]



Andrey and Raju demonstrated within world-line formalism that to capture the physics of anomaly we need to calculate everything in off-forward kinematics

Box diagram



Jaffe, Manohar (1990)

Calculation in off-forward kinematics $(l = p_2 - p_1)$:

$$\langle p_2 | J_5^\mu | p_1 \rangle = \frac{n_f \alpha_s}{4\pi} \frac{i l^\mu}{l^2} \langle p_2 | F_a^{\alpha\beta} \tilde{F}^a_{\alpha\beta} | p_1 \rangle$$

Triangle diagram is dominated by infra-red pole

Imprint of Anomalies in QCD Compton scattering

The role of the chiral anomaly in polarized deeply inelastic scattering I: Finding the triangle graph inside the box diagram in Bjorken and Regge asymptotics

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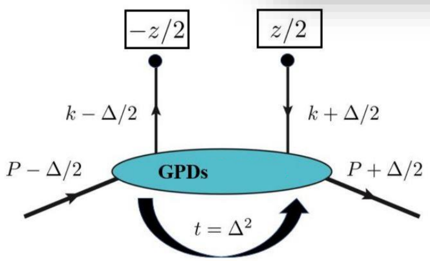
Topological screening and transitions fro[...]

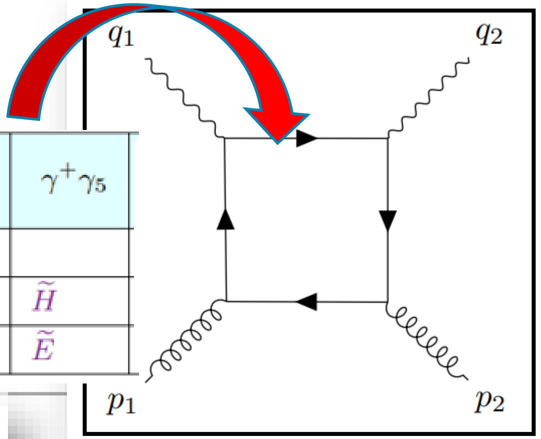
Andrey Tarasov[1,2] and Raju[...]

A fundamental pr[...]

Twist-2 GPDs



Pol. \ Γ	γ^+	$\gamma^+\gamma_5$
U	H	
L		$\widetilde{H}$
T	E	$\widetilde{E}$



Box diagram

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Jaffe, Manohar (1990)

Calculation in off-forward kinematics $(l = p_2 - p_1)$:

arXiv: 2210.13419 (2022)

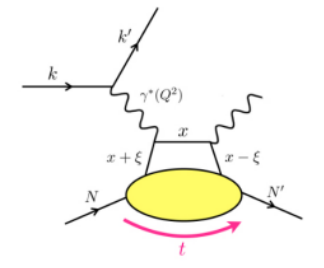
Chiral and trace anomalies in Deeply Virtual Compton Scattering

Shohini Bhattacharya,[1,*] Yoshitaka Hatta,[1,2,†] and Werner Vogelsang[3,‡]

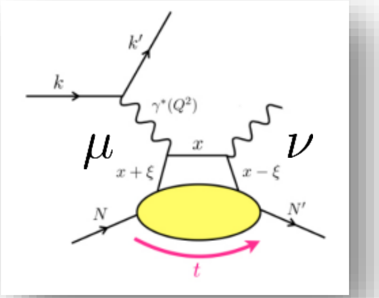
Perturbative Feynman-diagram approach:

Interpretation of results in terms of GPDs

Implication of anomaly poles on factorization of Compton scattering processes



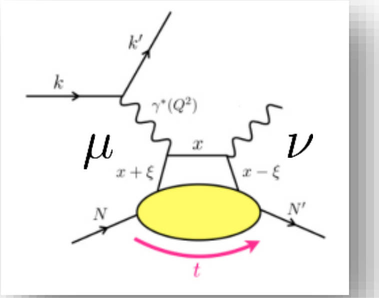
Imprint of Anomalies in QCD Compton scattering



Antisymmetric part of Compton amplitude $(\xi = 0)$

$$-\epsilon^{\alpha\beta\mu\nu} P_\beta \mathrm{Im} T^{\mathrm{asym}}_{\mu\nu}$$

Imprint of Anomalies in QCD Compton scattering



Antisymmetric part of Compton amplitude $(\xi = 0)$

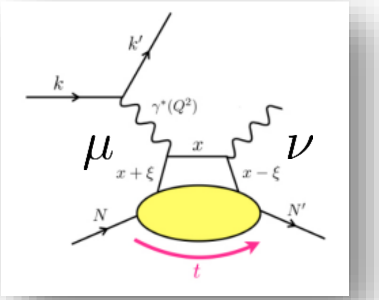
$$-\epsilon^{\alpha\beta\mu\nu} P_\beta \mathrm{Im} T^{\mathrm{asym}}_{\mu\nu} \approx \frac{1}{2}\frac{\alpha_s}{2\pi}\left(\sum_f e_f^2\right)\bar{u}(P_2)\left[\left(\Delta P_{qg} \ln\frac{Q^2}{-l^2} + \delta C_g^{\mathrm{off}}\right)\otimes \Delta G(x_B)\gamma^\alpha\gamma_5 + \frac{l^\alpha}{l^2}\delta C_g^{\mathrm{anom}} \otimes \tilde{\mathcal{F}}(x_B)\gamma_5\right]u(P_1)$$

Expected terms:

Splitting function $\Delta P_{qg}(\hat{x}) = 2T_R(2\hat{x}-1)$

Coefficient function $\delta C_g^{\mathrm{off}}(\hat{x}) = 2T_R(2\hat{x}-1)\left(\ln\frac{1}{\hat{x}(1-\hat{x})} - 1\right)$

Imprint of Anomalies in QCD Compton scattering



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Pole term
In agreement with Tarasov, Venugopalan

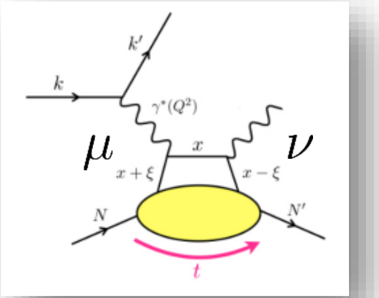
Coefficient function $\delta C_g^{\mathrm{anom}}(\hat{x}) = 4T_R(1-\hat{x})$

Twist-4 GPD:

$$\tilde{\mathcal{F}}(x,l^2) \equiv \frac{iP^+}{\bar{u}(P_2)\gamma_5 u(P_1)}\int\frac{dz^-}{2\pi}e^{ixP^+z^-}\langle P_2|F_a^{\mu\nu}(-z^-/2)\tilde{F}^a_{\mu\nu}(z^-/2)|P_1\rangle$$

Chiral anomaly manifests itself in high energy amplitude

Imprint of Anomalies in QCD Compton scattering



Antisymmetric part of Compton amplitude

$$-\epsilon^{\alpha\beta\mu\nu}P_\beta \mathrm{Im}T^{\mathrm{asym}}_{\mu\nu} \approx \frac{1}{2}\frac{\alpha_s}{2\pi}\left(\sum_f e_f^2\right)\bar{u}(P_2)\left[\left(\Delta P_{qg}\ln\frac{Q^2}{-l^2}+\delta C_g^{\mathrm{off}}\right)\otimes\Delta G(x_B)\gamma^\alpha\gamma_5 + \frac{l^\alpha}{l^2}\delta C_g^{\mathrm{anom}}\otimes\tilde{\mathcal{F}}(x_B)\gamma_5\right]u(P_1)$$

Twist-4 GPD

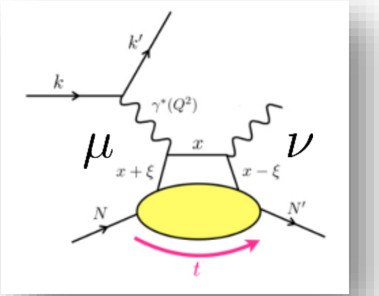
The QCD factorization theorem: Collins, Freund; Ji, Osborne (1998)

$$-\epsilon^{\alpha\beta\mu\nu}P_\beta \mathrm{Im}T^{\mathrm{asym}}_{\mu\nu} = \frac{1}{2}\sum_f e_f^2\bar{u}(P_2)\left[\gamma^\alpha\gamma_5(\tilde{H}_f(x_B,\xi,l^2)+\tilde{H}_f(-x_B,\xi,l^2))+\frac{l^\alpha\gamma_5}{2M}(\tilde{E}_f^{\mathrm{bare}}(x_B,\xi,l^2)+\tilde{E}_f^{\mathrm{bare}}(-x_B,\xi,l^2))\right]u(P_1)$$
$$+\mathcal{O}(\alpha_s)+\mathcal{O}(1/Q^2)$$

Twist-2 GPDs to all orders

Chiral anomaly manifests itself in high energy amplitude & possibly breaks QCD factorization

Imprint of Anomalies in QCD Compton scattering



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Anomalous contribution to GPD $\tilde{E}$ at one loop

The QCD factorization theorem: Collins, Freund; Ji, Osborne (1998)

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$$+\mathcal{O}(\alpha_s)+\mathcal{O}(1/Q^2)$$

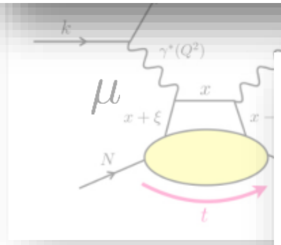
Twist-2 GPDs to all orders

Chiral anomaly manifests itself in high energy amplitude & possibly breaks QCD factorization

Imprint of Anomalies in QCD Compton scattering

Can we still justify factorization?

part of Compton amplitude



Redefine

$$\tilde{E}_f(x_B,l^2)+\tilde{E}_f(-x_B,l^2)=\tilde{E}_f^{\mathrm{bare}}(x_B,l^2)+\tilde{E}_f^{\mathrm{bare}}(-x_B,l^2)+\frac{\alpha_s}{2\pi}\frac{2M}{l^2}\delta C_g^{\mathrm{anom}}\otimes\tilde{\mathcal{F}}(x_B,l^2)$$

Tree level

One loop

$\tilde{E}$ at one loop

The QCD factorization theorem: Collins, Freund; Ji, Osborne (1998)

Postulate that the perturbative pole cancels the pre-existing pole in "bare" GPD:

$$\tilde{E}_f^{\mathrm{bare}}(x_B,l^2)+\tilde{E}_f^{\mathrm{bare}}(-x_B,l^2)\approx-\frac{\alpha_s}{2\pi}\frac{2M}{l^2}\delta C_g^{\mathrm{anom}}\otimes\tilde{\mathcal{F}}(x_B,l^2=0)$$

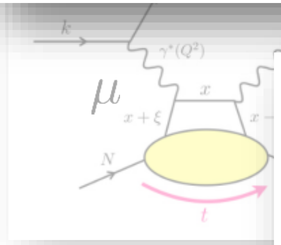
Postulate that the "renormalized" GPD integrates to $g_P(l^2)$:

$$g_P(l^2)=\sum_f\int_{-1}^{1}dx\tilde{E}_f(x,\xi,l^2)=\sum_f\int_0^1 dx(\tilde{E}_f(x,\xi,l^2)+\tilde{E}_f(-x,\xi,l^2))$$

amplitude &

Imprint of Anomalies in QCD Compton scattering

Can we still justify factorization? part of Compton amplitude



Redefine

$$\tilde{E}_f(x_B,l^2)+\tilde{E}_f(-x_B,l^2)=\tilde{E}_f^{\rm bare}(x_B,l^2)+\tilde{E}_f^{\rm bare}(-x_B,l^2)+\frac{\alpha_s}{2\pi}\frac{2M}{l^2}\delta C_g^{\rm anom}\otimes\tilde{\mathcal{F}}(x_B,l^2)$$

Tree level

One loop

$C_g^{\rm anom}\otimes\tilde{\mathcal{F}}(x_B)\gamma_5\Big]u(P_1)$

$\tilde{E}$ at one loop

The QCD factorization theorem: Collins, Freund; Ji, Osborne (1998)

Consistency:

$$T_{\mu\nu}^{\rm asym}=\frac{1}{2}\sum e_f^2\bar{u}(P_2)\Big[\gamma^\alpha\gamma_5(\tilde{H}_f(x_B,\xi,l^2)+\tilde{H}_f(-x_B,\xi,l^2))+\frac{l^\alpha\gamma_5}{2M}(\tilde{E}_f^{\rm bare}(x_B,\xi,l^2)+\tilde{E}_f^{\rm bare}(-x_B,\xi,l^2))\Big]u(P_1)$$

We find:

$$\frac{g_P(l^2)}{2M}=-\frac{i}{l^2}\left(\frac{\langle P_2|\frac{n_f\alpha_s}{4\pi}F\tilde{F}|P_1\rangle}{\bar{u}(P_2)\gamma_5u(P_1)}\Bigg|_{l^2=0}-\frac{\langle P_2|\frac{n_f\alpha_s}{4\pi}F\tilde{F}|P_1\rangle}{\bar{u}(P_2)\gamma_5u(P_1)}\right)$$

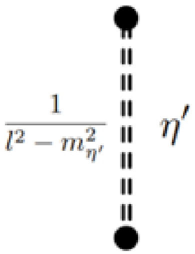
Exactly the scenario mentioned by Jaffe-Manohar & Tarasov-Venugopalan

Conversion of massless pole to massive pole:

$$\frac{g_P(l^2)}{2M}\approx\frac{-2M\Delta\Sigma}{l^2-m_{\eta'}^2}$$

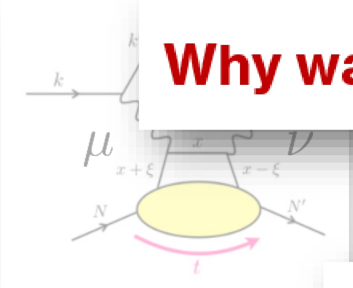
fest ... high energy amplitude &

bre ... factorization



Imprint of Anomalies in QCD Compton scattering

Why was the pole unnoticed in literature?



$$-\epsilon^{\alpha\beta\mu\nu} P_\beta \mathrm{Im}T^{\mathrm{asym}}_{\mu\nu} \approx \frac{1}{2}\frac{\alpha_s}{2\pi}\left(\sum_f e_f^2\right)\bar{u}(P_2)\left[\left(\Delta P_{qg}\ln\frac{Q^2}{-l^2}+\delta C_g^{\mathrm{off}}\right)\otimes\Delta G(x_B)\gamma^\alpha\gamma_5+\frac{l^\alpha}{l^2}\delta C_g^{\mathrm{anom}}\otimes\tilde{\mathcal{F}}(x_B)\gamma_5\right]u(P_1)$$

at one loop

The QCD facto

Pole was unnoticed in the GPD literature because one typically assumes

$$l^\mu = -2\xi p^\mu \;\rightarrow\; t = l^2 = 0$$

before loop integration

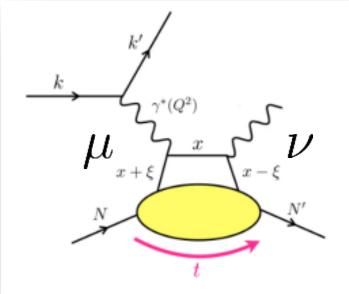
Usual rationale: Corrections supposedly higher twist $\dfrac{t}{Q^2}$

$-\epsilon^{\alpha\beta\mu\nu}P_\beta \mathrm{I}$ … $u(P_1)$

Twist-2 GPDs to all orders

Chiral anomaly manifests itself in high energy amplitude & possibly breaks QCD factorization

Imprint of Anomalies in QCD Compton scattering

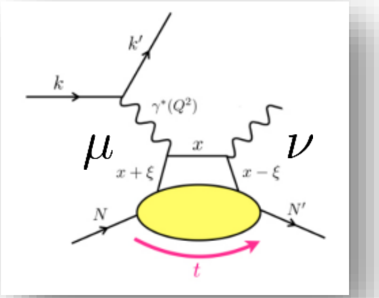


Symmetric part of Compton amplitude $(\xi \neq 0)$

Example:

$$\bar{F}_1^{\mathrm{off}}(x_B, l)$$

Imprint of Anomalies in QCD Compton scattering



Symmetric part of Compton amplitude $(\xi \neq 0)$

Pole! (New result)

Example:

$$\bar{F}_1^{\mathrm{off}}(x_B, l) \approx \frac{1}{2}\frac{\alpha_s}{2\pi}\left(\sum_f e_f^2\right)\left[\left(P_{qg}\ln\frac{Q^2}{-l^2} + C_{1g}^{\mathrm{off}}\right)\otimes g(x_B) + \frac{1}{l^2}C^{\mathrm{anom}}\otimes' \mathcal{F}(x_B,\xi,l^2)\frac{\bar{u}(P_2)u(P_1)}{2M}\right]$$

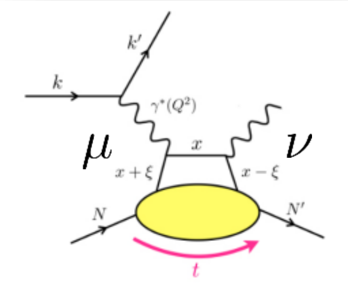
Twist-4 GPD:

$$\mathcal{F}(x,\xi,l^2) = -4xP^+M\int\frac{dz^-}{2\pi}e^{ixP^+z^-}\frac{\langle P_2|F^{\mu\nu}(-z^-/2)F_{\mu\nu}(z^-/2)|P_1\rangle}{\bar{u}(P_2)u(P_1)}$$

Chiral anomaly	Trace anomaly
Anomaly equation: $\partial_\mu J_5^\mu = -\frac{n_f\alpha_s}{4\pi}F^{\mu\nu}\tilde{F}_{\mu\nu}$	**Anomaly equation:** $\Theta_\mu^\mu = \frac{\beta(g)}{2g}F^{\alpha\beta}F_{\alpha\beta}$ $\Theta^{\mu\nu}$ **: EMT**
Form Factors: $(g_A,\, g_P)$	**Gravitational Form Factors:** $(A,\, B,\, \bar{C},\, D)$

Trace anomaly manifests itself in high energy amplitude & possibly breaks QCD factorization

Imprint of Anomalies in QCD Compton scattering



Symmetric part of Compton amplitude $(\xi \neq 0)$

Example:

Pole! (New result)

$$\bar{F}_1^{\rm off}(x_B, l) \approx \frac{1}{2}\frac{\alpha_s}{2\pi}\left(\sum_f e_f^2\right)\left[\left(P_{qg}\ln\frac{Q^2}{-l^2} + C_{1g}^{\rm off}\right)\otimes g(x_B) + \frac{1}{l^2}C^{\rm anom}\otimes' \mathcal{F}(x_B,\xi,l^2)\frac{\bar{u}(P_2)u(P_1)}{2M}\right]$$

Anomalous contribution to GPDs $H,\ E$ at one loop

Twist-4 GPD:

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Trace anomaly manifests itself in high energy amplitude & possibly breaks QCD factorization

Imprint of Anomalies in QCD Compton scattering

Symmetric part of Compton amplitude $(\xi \neq 0)$

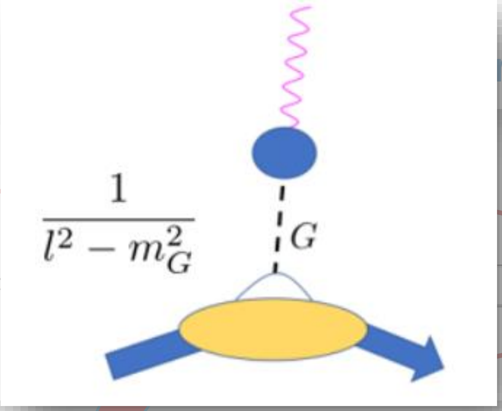
Pole! (New result)

We proposed a possible scenario of pole cancellation in an attempt to rescue QCD factorization

anomalous contribution to GPDs H, E at one loop

Twist-4

$$\mathcal{F}(x,\xi,l^2) = -4xP^+M\int\frac{dz^-}{2\pi}e^{ixP}$$



glueball mass generations

Trace anomaly manifests itself in high energy amplitude & possibly breaks QCD factorization

Summary

- **QCD factorization for Compton scattering: Backbone of the GPD programs at ongoing & future experiments including EIC**

- **Unexpected contributions originating from chiral & trace anomalies**

$$T^{\mu\nu} \sim \frac{\langle F^{\alpha\beta}\tilde{F}_{\alpha\beta}\rangle}{l^2}, \quad \frac{\langle F^{\alpha\beta}F_{\alpha\beta}\rangle}{l^2}$$

Unnoticed in literature, possible violation of factorization

Summary

Perturbative calculations suggest that massless poles are induced in GPDs $\tilde{E},\ H,\ E$

However, we know there are no massless poles in axial and gravitational form factors (moments of GPDs)

- Unexpected contributions originating from chiral & trace anomalies

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Summary

Perturbative calculations suggest that massless poles are induced in GPDs $\tilde{E},\ H,\ E$

However, we know there are no massless poles in axial and gravitational form factors (moments of GPDs)

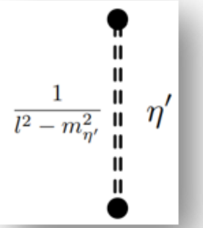
- **We proposed a possible scenario of pole cancellation** trace anomalies

This has to do with eta-meson & glueball mass generations

Antisymmetric case:

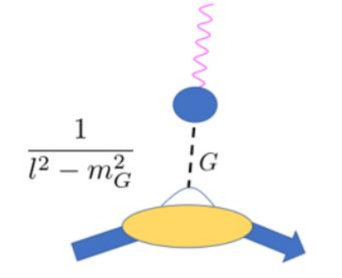
Unnoticed

cf, the η' mass problem



$$g_P \sim \int dx \tilde{E}(x) \sim \frac{1}{l^2 - m_{\eta'}^2}$$

Symmetric case:



Summary & outlook

Perturbative calculations suggest that massless poles are induced in GPDs $\tilde{E},\ H,\ E$

However, we kno... ...rs (moments of GPDs)

Novel connections between DVCS & chiral/trace anomalies:
This could be a new & potentially rich avenue for GPD research

- We prop... pole cancellation ... trace anomalies

Higher-loop calculations

This has to do with eta-meson & glueball mass generations

Antisymme...

Imprint of anomaly on other physical processes:

(Example: Deeply-virtual meson production)

Unnoticed

$$g_P \sim \int dx \tilde{E}(x) \sim \frac{1}{l^2 - m_{\eta'}^2}$$

Symmetric case: